

# ORIGINS

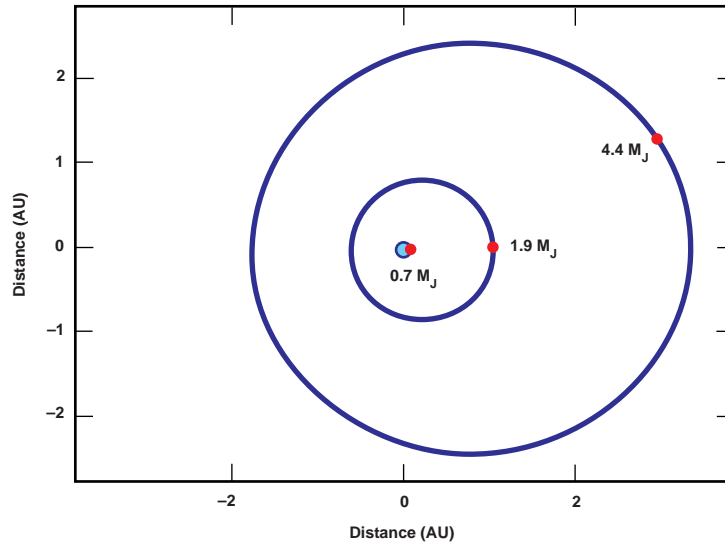
S C I E N T I F I C G O A L S

The past three decades have witnessed major strides in our efforts to understand the way in which stars and planetary systems form. Observations using both ground- and space-based facilities have permitted us to look inside the nurseries where stars are being born. In concert with these observations, studies of the Solar System through space missions and analysis of meteorites have provided us with clues to the conditions and processes that shaped the early evolution of our own planetary system. These advances, taken together, have allowed us to formulate a theory of how stars and planetary systems form.

If this theory is correct, we would expect that most, if not all, single stars should have planetary systems. We have ample indirect evidence for the existence of planetary mass companions around other stars, based on the detection of wobble in the motions of those stars thought to be caused by the gravitational forces of orbiting companions. More direct evidence has been found in one case, where astronomers observed the decrease in stellar brightness caused by the transit of a planet across the face of the star. However, these newly discovered systems are unlike our Solar System. The deduced companions have masses comparable to (or greater than) those of our most massive planets, Jupiter and Saturn, but have orbits that are closer to their central stars than the giant planets in our Solar System. We have not yet found an exact analog to our planetary system.

2 TO  
UNDERSTAND  
HOW  
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AND  
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AND  
EVOLVE.

The list of stars for which radial velocity variations indicate the presence of companions in the Jupiter-mass range has increased to over 30, including the remarkable system Upsilon Andromedae, which shows evidence for three such companions. Minimum masses are indicated in the figure.



Because of the limitations of the spectroscopic technique used to discover these systems, we do not yet have an unbiased and statistically complete census of planetary systems. In order to refine and extend our understanding of how planetary systems form, we must continue the search for planets with a wide variety of techniques and interpret the results with theoretical studies.

**OBJECTIVE 3 • Discover planetary systems forming around young stars, and characterize their properties.**

Observations at infrared and longer wavelengths have done much in the past three decades to reveal the stages that interstellar gas and dust pass through along the way to forming stars and planetary systems. Theoretical studies of the type supported by the Research and Analysis (R&A) program provide an overall framework for understanding the many manifestations that protostars exhibit before becoming mature stars like the Sun. These theories also predict some of the properties that are expected for phases of the star-formation process that are not observable with current instruments and detectors.

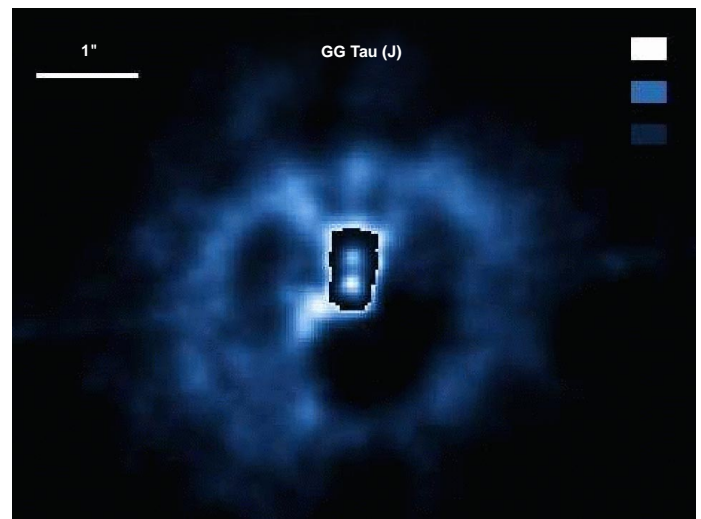
We now have observational evidence relating to most of the stages of star formation. These stages include dense cores in molecular clouds that are on the verge of gravitational collapse, newly formed protostars, young stellar objects with gas-rich circumstellar disks, and main-sequence stars surrounded by tenuous dust disks that remain after the disk gas has been dispersed.

Disk properties can be deduced from observations at infrared and millimeter wavelengths, and ground-based millimeter-wave interferometers are beginning to probe structures on scales relevant to planetary system formation. Observations of gaps, warps, waves, and holes in disks could provide indirect evidence for the presence of planetary bodies in these systems. Such clues will lead to the direct detection of newly formed planets in circumstellar disks around young stars.

### INVESTIGATIONS FOR OBJECTIVE 3

***Investigation 5: Understand why molecular clouds produce mainly multiple star systems rather than single stars like the Sun.***

The evolution of a young star begins with the collapse of a rotating, somewhat turbulent, magnetized core of a molecular cloud. At least some of the initial angular momentum of that core later appears as the orbital motion of the components of a binary star or of a disk surrounding a single star, or as one of the components of the binary. Observed binary and multiple systems exhibit a wide range of orbital periods, eccentricities, and mass ratios. The mechanism by which they form is not well



A ground-based image of the disk surrounding the young binary-star system GG Tau.



This near-infrared  
2MASS image of  
the stellar nursery  
Mon R2 shows a  
few hundred  
young stars.

understood, but there is much observational evidence in favor of the hypothesis that they form by fragmentation, induced by rotational effects during the collapse. The frequency of the occurrence of planets depends on the nature of these multiple systems — most stars are contained in them, and conditions in their disks are not always favorable for planet formation.

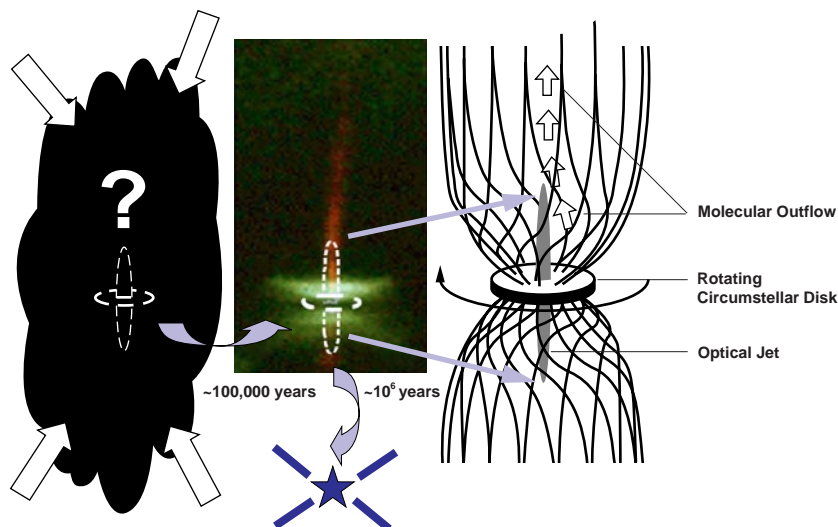
Also not well understood are the circumstances under which single stars, rather than multiple systems, are formed. It is possible that the outcome depends on the initial conditions in a molecular cloud core. Alternatively, cloud collapse could result in a small multiple system, one of whose components is later ejected as a result of a close gravitational encounter.

To understand the different modes of star formation, we must continue a vigorous R&A program that investigates the collapse and fragmentation of molecular clouds and

the formation and properties of circumstellar disks around both single- and multiple-star systems. In order to determine the infall and rotational motions of the collapsing gas and to provide clues on the earliest phases of binary- and single-star formation, we must perform continuum and spectral-line observations at angular resolutions of 0.1–1 arcsec (10–100 AU in the nearest star-forming regions). In the mid- to far-infrared (30–300  $\mu\text{m}$ ), FAIR will be able to determine the temperature, density, and velocity structure of collapsing cloud cores (both with and without central protostars) by mapping the emission from the dominant gas coolants (OI,  $\text{H}_2\text{O}$ , C+, high-J CO lines). At shorter IR wavelengths, NGST will be able to probe the most central regions of protostars.

***Investigation 6: Determine how planetary-system-forming disks evolve.***

The life history of a disk surrounding a young star must be determined through a combination of theory and observation. It has been determined observationally that stars accrete material from the disks, that the observable disks around young stars have finite lifetimes of at most a few million years, and that the disks are generally associated with



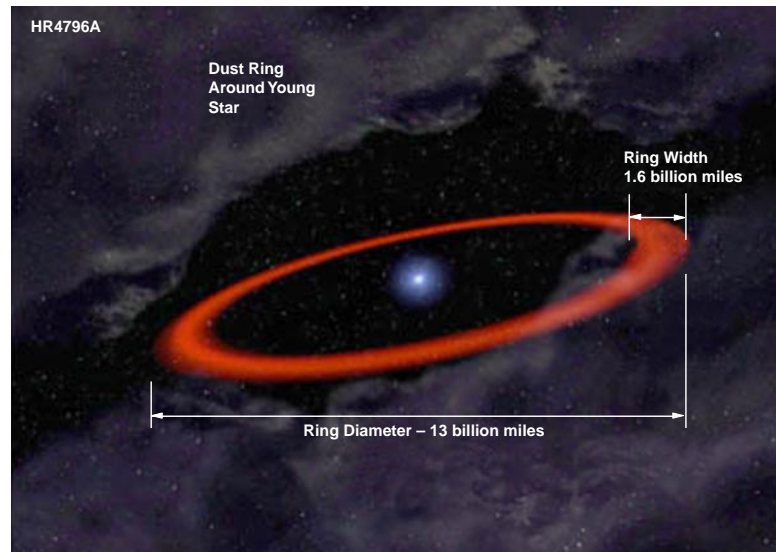
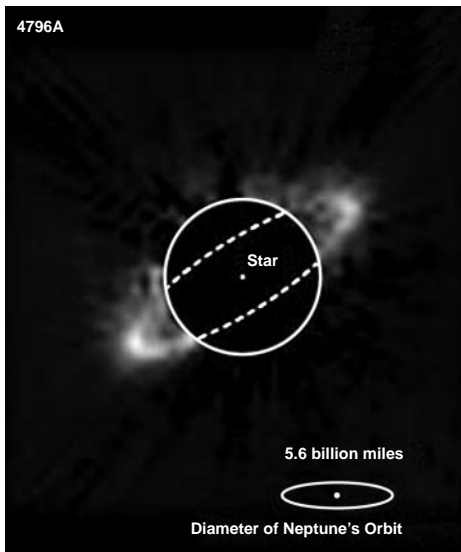
Disks of gas and dust, with associated jets and outflows, form as rotating molecular clouds collapse into stars.

highly collimated bipolar outflows (jets). There is observational evidence for two constituents of the disk material: the gas (primarily molecular hydrogen) and the dust, representing interstellar grains incorporated into the disk. The dust is the key to forming planets like the Earth and it likely plays a critical role in the formation of giant planets as well.

An artist's  
concept of a  
protoplanetary  
disk forming  
around a  
nascent star.

A number of physical processes are thought to drive the disk evolution, including gravitational instability, turbulent viscosity, magnetic torques, and dissipation by the action of outflows and UV photons. As the disk evolves, dust grains collide, stick together, and sediment to the midplane of the disk, where they become the building blocks of the planets. Later, the gravitational interaction of the growing planets with the disk leads to the formation of spiral waves and gaps and to the inward migration





of the planets. Many aspects of this schematic picture remain unclear. A robust R&A program in theoretical and computational astrophysics is necessary to refine our ability to interpret the observational data.

The detection of gaps and spiral waves in protoplanetary disks and the study of the interaction between outflows and disks will require extremely high-angular-resolution observations. The expected spatial scales range from 0.1 AU in the inner disk (which radiates in the near-infrared at a few microns) to 1 AU in the outer disk (which radiates in the far infrared at 100  $\mu\text{m}$ ). These spatial scales correspond to angular resolutions of 0.001–0.01 arcsec in the nearest star-forming complexes, and are achievable only with space-based interferometers with baselines of a few kilometers that span the infrared spectral region. The high angular resolution of TPF will play an essential role in mapping planet-induced disk structure in the inner disk. A far-infrared interferometer will be needed to study the cool outer regions of disks.

As the formation of a disk–planet system comes to completion, the remnant disk gas is dispersed, leaving behind planets and the rubble of many smaller bodies. Dust produced

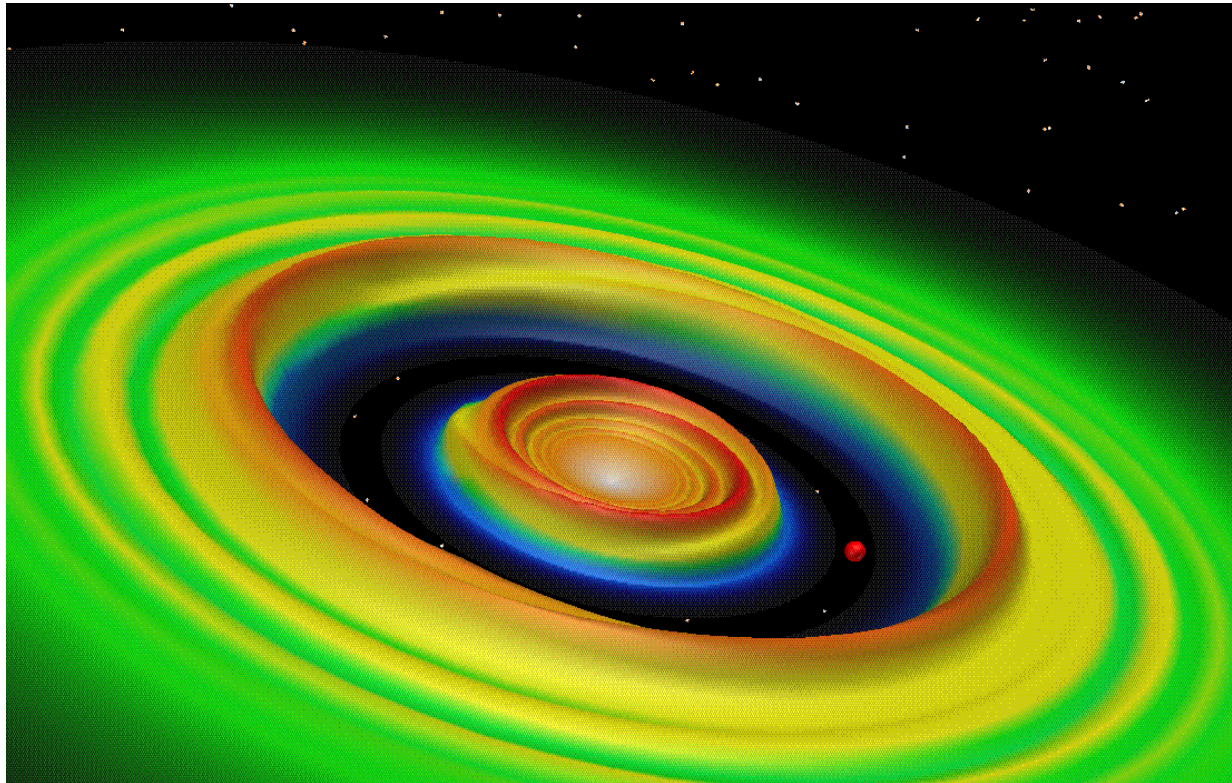
Remnant dust rings, perhaps the debris from the construction of planets, have been seen around many nearby stars.

from this planetary debris is thought to be responsible for the low-mass disks that have been detected around more mature stars, such as Vega and Beta Pictoris. The overall scale of these structures is relatively large; for example, the debris disk around HR 4796A has a ringlike geometry with a maximum intensity about 1 arcsec from the star (70 AU) and a width of 0.25 arcsec. FAIR is ideally suited to map the structure in debris disks around nearby main-sequence stars, which may provide evidence for the presence of planets revolving around these stars. Spatially resolved spectroscopy with FAIR can also probe the mineralogy of the debris disks using the 20- to 35- $\mu\text{m}$  signatures of crystalline and amorphous silicates and the 63- $\mu\text{m}$  emission feature of ice.

This theoretical model shows how a planet might carve a gap in the disk surrounding a forming star.

***Investigation 7: Search for evidence of planet formation in disks around young stars.***

One way of deducing the existence of planetary formation processes in disks is to find evidence that small dust grains are being depleted by coagulation into larger grains



and eventually into planetesimals. Observations must be devised that are capable of distinguishing depletion due to grain growth from that which may be caused by radiation blowout and Poynting-Robertson drag. Spectral and photometric studies, using NGST and FAIR, of the temporal development of the IR spectral energy distributions of the disks around young stars play central roles in this Investigation.

As planets form from the dust disk, they can interact gravitationally with the remaining gas. For relatively small planetary masses (10–100 Earth masses), this interaction results in density waves; for masses comparable to that of Jupiter, it results in the opening of gaps in the disk, with a radial extent of a few tenths of an astronomical unit or greater. These disk signatures may serve as proxies for the underlying planet, which may be much more difficult to detect directly. The detection of a gap of 1 AU width, at a distance of 5 AU from a star in a nearby star-forming region, will require an angular resolution better than 0.01 arcsec. The gap and planet will be separated from the star by only 0.05 arcsec, and for typical disk and planetary temperatures of a few hundred kelvins, most of the energy is radiated in the 10- $\mu$ m spectral region. Interferometric imaging of disks in nearby star-forming regions by TPF, using baselines up to a kilometer, will be able to map these disk structures and give us an unprecedented view of the planet-formation process.

Another approach to the detection of young protoplanets is direct imaging of the objects, which, according to some theoretical models, may achieve a brightness of 1/1000 to 1/100 that of the central star during a relatively brief phase of rapid accretion of gas. A Jupiter-like protoplanet at 5 AU from its star will be separated from the star by 0.05 arcsec at distances of 100 pc. The starlight nulling ability of TPF will be essential to separate the planetary radiation from that of the surrounding disk and the star.

**OBJECTIVE 4 • Characterize the planets and planetary systems around other stars.**

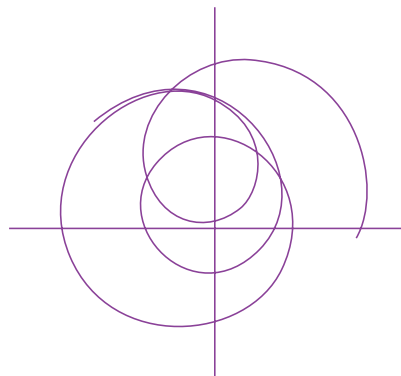
Research during the latter half of the 20th century has led to the development of a generally accepted theory of how stars and planetary systems form. While this theory is a major advance over its counterparts from the beginning of the century, it is a fabric that contains many holes. The theory, which is based on observations of the Solar System, does not tell us which, if any, properties of this system are representative of planetary systems in general. This issue will only be addressed when we have conducted a survey of a statistically significant number of stars for the presence of planetary systems and have observed them sufficiently to infer the masses and orbital properties of the planets in those systems.

The overall theory suggests that objects similar in mass and composition to Earth may exist in many planetary systems. Detection of such planets and the spectroscopic analysis of the temperature and composition of their atmospheres is a key objective of the search for planetary systems. One step toward the detection of such planets could be the identification of systems that are analogs of the Solar System in which giant planets (if present) orbit well beyond the habitable zone.

The presence of a planet orbiting a star causes small shifts in the position of the star over the years. This subtle shift is detectable with the hyperprecision of KIA and SIM.

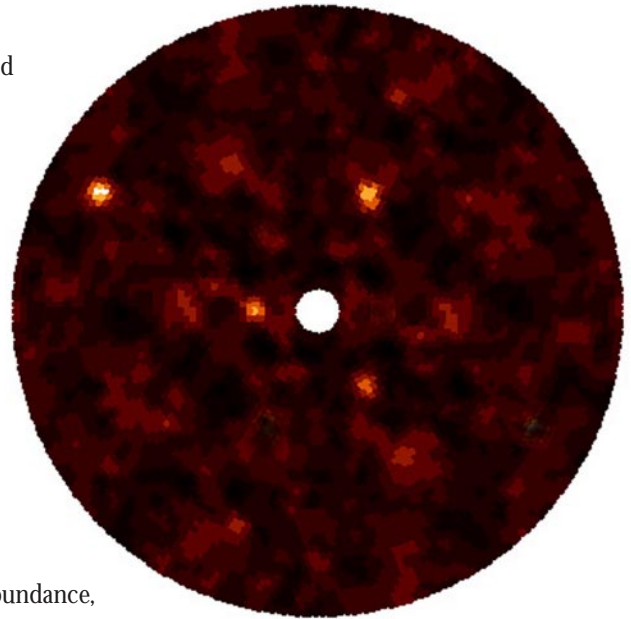
**INVESTIGATIONS FOR OBJECTIVE 4**

***Investigation 8: Search for planetary systems around a variety of stars, and determine the orbits, masses, temperatures, and atmospheric composition of their planets.***



We must conduct an extensive census of main-sequence stars to determine the orbital characteristics and gross physical properties of extrasolar planets. As a first phase, we need to make a complete inventory of all nearby stars

and a statistically significant sample of more distant stars to find all Jupiter-mass planets and as many Neptune-mass planets as possible. This search will require radial velocity precision of 1 m/s or better (KIA), astrometric precision of 1–10 microarcsec (SIM), photometric precision of 0.001 magnitude, and the ability to image planets having an infrared brightness only a millionth that of a star from which it is separated by less than a tenth of an arcsecond (TPF). Such a survey will reveal the dependence of planet formation on stellar properties such as mass, heavy-element abundance, angular momentum, and magnetic field, and may well tell us when in the history of the galaxy the earliest planets formed.



As a second phase, spectra will be obtained from those giant planets that have been imaged, so that temperatures and atmospheric composition can be determined. TPF will be able to observe the characteristic spectral features of water, carbon dioxide, methane, and ammonia. This information will provide important evidence about the formation processes in these systems.

Finally, the survey should be extended down toward the Earth-mass range so that the frequency of Earth-like planets and their characteristics can be estimated. Radial velocity programs are unlikely to detect extrasolar planets with masses below a Uranus mass. Astrometric searches with an accuracy of 10 microarcsec (KIA) to 1 microarcsec (SIM) can push the limit down to a few times the Earth mass and survey a volume out to 5–10 pc. A space-based photometric survey can extend to much larger volumes of space and can provide an initial estimate of the frequency of planets in this mass range. But direct imaging and eventual spectroscopy will require an interferometer such as TPF that can null the light of the central star to a part in 100,000 to 1,000,000.

TPF will be able to image whole planetary systems that may orbit nearby stars, including planets as small as Earth. In this image, the light from the central star is blocked so that faint orbiting planets show as points of light.